Track-to-track data fusion for Unmanned Traffic Management System

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Abstract—**The growing need of large scale sensor networks for tracking of Unmanned Aerial Systems (UAS) results in high demand of effective algorithms which will provide automatic data fusion and produce human readable results. This paper presents a track-to-track data fusion system, where data from two independent sources are used to track Unmanned Aerial Vehicles (UAVs). The first source of data is Cooperative Surveillance System (CSS) trackers for UAVs, and the second source is Independent Non-cooperative Surveillance (INCS) from a ground based staring radar. The paper provides details on the whole process including: data pre-processing, association, analysis, fusion and output processing. Metrics and their influence on tracking results are also explained. Results of track-to-track data fusion of real-life experimental flight tests are provided.**

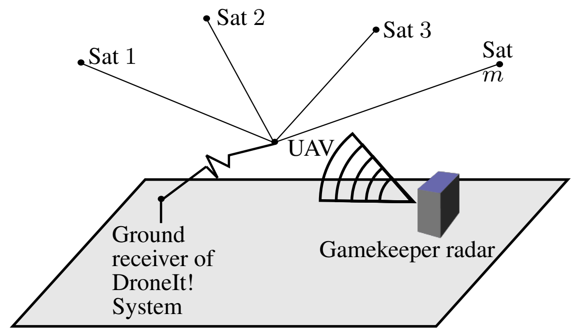

Figure 1. Radar and tracker - operation concept.

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1. INTRODUCTION

The work on track-to-track data fusion for Unmanned Traffic Management System (UTMS) has been carried out under the Single European Sky ATM Research (SESAR) Joint Undertaking [1] project: Ground based technologies for a real-time unmanned aerial system traffic management system (UTMS) within the CLASS (CLear Air Situation for uaS) project [2].

The CLASS projects includes cooperation of 5 international partners. The CLASS project uses Aveillant Gamekeeper 16U radar (Figure 2) to detect non-cooperative UAVs, and Airbus system Drone-it! (Figure 3) to track cooperative vehicles. Norwegian University of Science and Technology (NTNU) is involved in data-fusion activities, while system's user interface is created by Unifly. French Civil Aviation University (ENAC) were operating UAVs during experiments discussed in this paper.

The CLASS project goal is to merge existing technologies to create the core functions of UTMS. Use of Unmanned Aerial Vehicles (UAVs), also known as "drones" or Unmanned Aerial Systems (UAS), is rising in popularity over the last decade. Advancements in control electronics, as well as miniaturization and efficiency increase of electric motors, batteries, and payload systems have boosted the popularity of UAVs in many fields of industry, research, and even for social purposes. The trends in UAV technologies suggest that the low altitude airspace could be significantly populated by different kind of drones in the near future [3]. The main challenge of the CLASS project is that UAVs are generally small flying objects, operating at low altitudes, which implicate that they are hard to detect in existing air traffic control systems. The availability of automated Detect And Avoid (DAA) functions, in addition to more reliable means of communication, should lead to a significant increase of safety of operations.

The DAA systems could be cooperative, and non-cooperative. Cooperative systems requires an UAV to carry a specialized transponder providing information about its location in space over a standardized communication channel. In non-cooperative systems UAVs positions are observed and tracked by an external system. The objectives of the CLASS project, where track-to-track data fusion is used, include real-time tracking and display of both cooperative and non-cooperative targets, simultaneously filtering out non-UAV objects, such as birds. The CLASS project addresses U-space[4] services on the level of U1, U2 and U3[5]:

- U1 - include e-registration, e-identification and geo-

Figure 2. Aveillant Gamekeeper 16U, Counter-UAS radar. Photo courtesy of Aveillant.

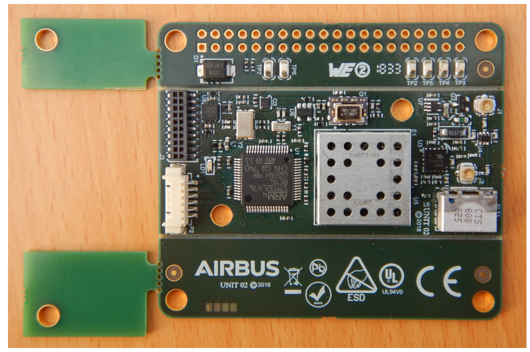

Figure 3. Airbus Drone-it! prototype board.

Figure 4. Aveillant DJI Inspire drone.

fencing.
- U2 - initial services support - the management of drone operations and may include flight planning, flight approval, tracking, airspace dynamic information, and procedural interfaces with air traffic control.
- U3 - advanced services support - more complex operations in dense areas and may include capacity management and assistance for conflict detection.

In this paper the flight data sources are inputs from the UAV transponders, and ground based radar. These technologies allows to create a real-time centralized UTMS that is scaleable, and should be able to fulfill needs of current and future UAVs traffic. The results of the project could be used by the parties interested in providing advanced services such as geo-fencing, geo-caging, traffic conflict detection and resolution.

Track-to-track association and fusion problems involves several challenges. In practical systems, such as the setup considered here, it may not be possible to assume that reliable information about the uncertainty accompanies the tracks from the cooperative and non-cooperative tracking systems. That is however, not compatible with the requirements of many of the methods available in the literature. Another requirement is real-time data processing, which means that a computationally efficient method should be used. On the other hand, if the data fusion engine will work with the assumption that it can accept a few seconds of latency, then it is possible to achieve higher quality of the fused data points. For example, in mentioned version of algorithm with latency there is no need of using approximate extrapolation and it can use interpolation of cooperative detection points to the higher rate of the radar (radar update rate is up to 4 Hz and transponder update rate is 0.5 Hz). Since lack of reliable information about the quality and accuracy of the data sources, another challenge is choosing which of the sources the track-to-track data fusion system should trust more. A natural first choice is to trust cooperative transponder more than the radar system. This scenario is based on assumptions that the transponder is on-board a certain drone, where it has its own identifier and positioning data comes from global navigation satellite systems (GNSS). The radar may be more uncertain, and exposed to produce false positives, and higher level of noise in positioning. However, there are certain situations in which radar signal can provide better accuracy.

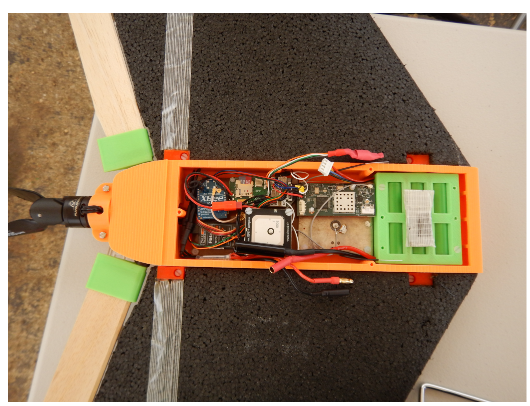

Figure 5. ENAC's Zagi UAV with integrated Drone-it! system.

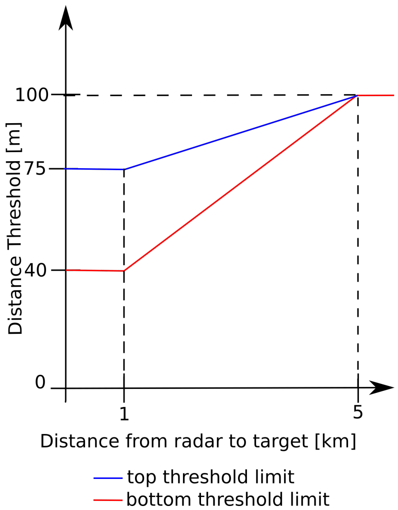

Figure 6. Threshold function chart.

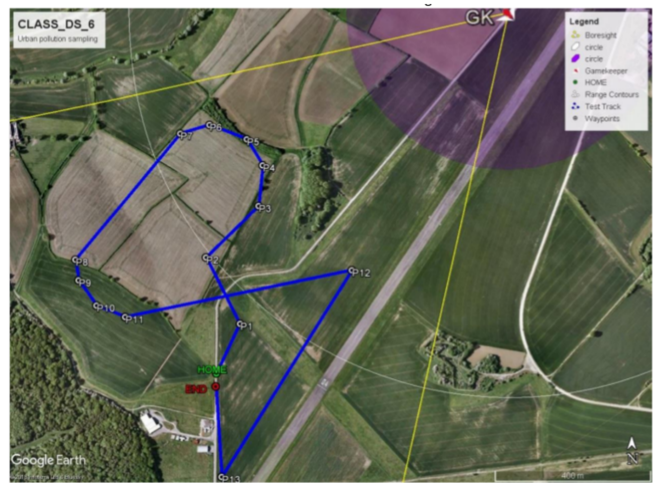

Figure 7. UAV flight plan during the experiment. Graphics courtesy of Aveillant.

For example, GNSS signal can be influence by interference, jammed, or spoofed. Furthermore, radar will see all drones, not only those carrying a transponder.

Track-to-track association and fusion problems of different tracking systems with various characteristics has been extensively studied in the literature. NASA is researching prototype technologies for a UAS Traffic Management (UTM) system that could develop airspace integration requirements for enabling safe, efficient low-altitude operations, [6, 7]. In [8] an optimal track-to-track fusion was described. The solutions for data out of synchronization from multiple sensors are described in [9–11]. Technical issues associated to several different architectures of track fusion are deeply described and compared in [12, 13]. Hierarchical fusion architecture including fusion information matrix algorithm is described in [14, 15].

In this paper, the concept of a track-to-track data fusion for UTMS is presented using a combination of arbitration/statistic functions, and is validated experimentally. The experimental demonstration is carried out by comparing results from the data fusion engine based on radar and transponder data with reference data from autopilot log.

Section 2 presents technology components of the CLASS project. The track-to-track data fusion algorithm is presented in Section 3. Section 4 describes the experiment and discusses its results.

2. The CLASS project

The concept of operation of the system is illustrated in Figure 1.

Aveillant Gamekeeper 16U radar [16] is able to detect, track and classify the small Unmanned Aerial Systems (sUAS) in 3D space, in range up to 5 kilometers from its position. This radar floodlights the entire space in its filed-of-view, with use of an array of fixed, staring receivers to create a 3D map of detected objects in the surrounding airspace, which also include velocity of every object. The radar software analyzes all kinds of detections, which need to be further filtered and classified using a set of features. Using its staring array design, high update rate, fine Doppler technology, and 3D feature, the radar is able to detects small, slow but agile objects which fly low. The principles of Aveillant radar technology are described in [17], however mentioned paper describes older prototype version of the radar and the system.

Airbus Drone-it! is a dedicated terminal device for UAVs, working at L-band, encapsulated in small (credit card size device) and light casing, equipped with its own battery, and designed to be attached to any kind of UAV. The device is based on an IoT technology, enabling communication using small encrypted packets. The device can be used as a transponder for drones where, e.g. ADS-B technology may not fulfill needs of future high density traffic. The terminal is part of the Cooperative Surveillance System (CSS) Drone-it! developed by Airbus.

NTNU's task in CLASS is involved in development of track-to-track data fusion system, which will process output data from Aveillant Gamekeeper radar and Airbus Drone-it! system.

Unifly develops real-time situational awareness system which is visualizing output of CLASS project systems. That include output from radar, transponder, data fusion results, and raw data from ground control station of UAV. The data is available to the users via a web interface.

French Civil Aviation University (ENAC) UAS team role, during field tests, was integration of CSS Drone-it! into UAS and performing UAV (Figure 5) operations based on predefined flight scenarios. ENAC was also responsible for specifying the flight profiles for drones used in field tests.

In this paper data logged by Avillant DJI Inspire UAV 4 is used as a ground truth for metrics calculation.

3. Algorithm description

An overview of the data fusion engine is given in Figure 8, and described in more detail in the next paragraphs.

Data input processing

The track-to-track data fusion engine has two input data sources. Both of them are encoded into Eurocontrol binary

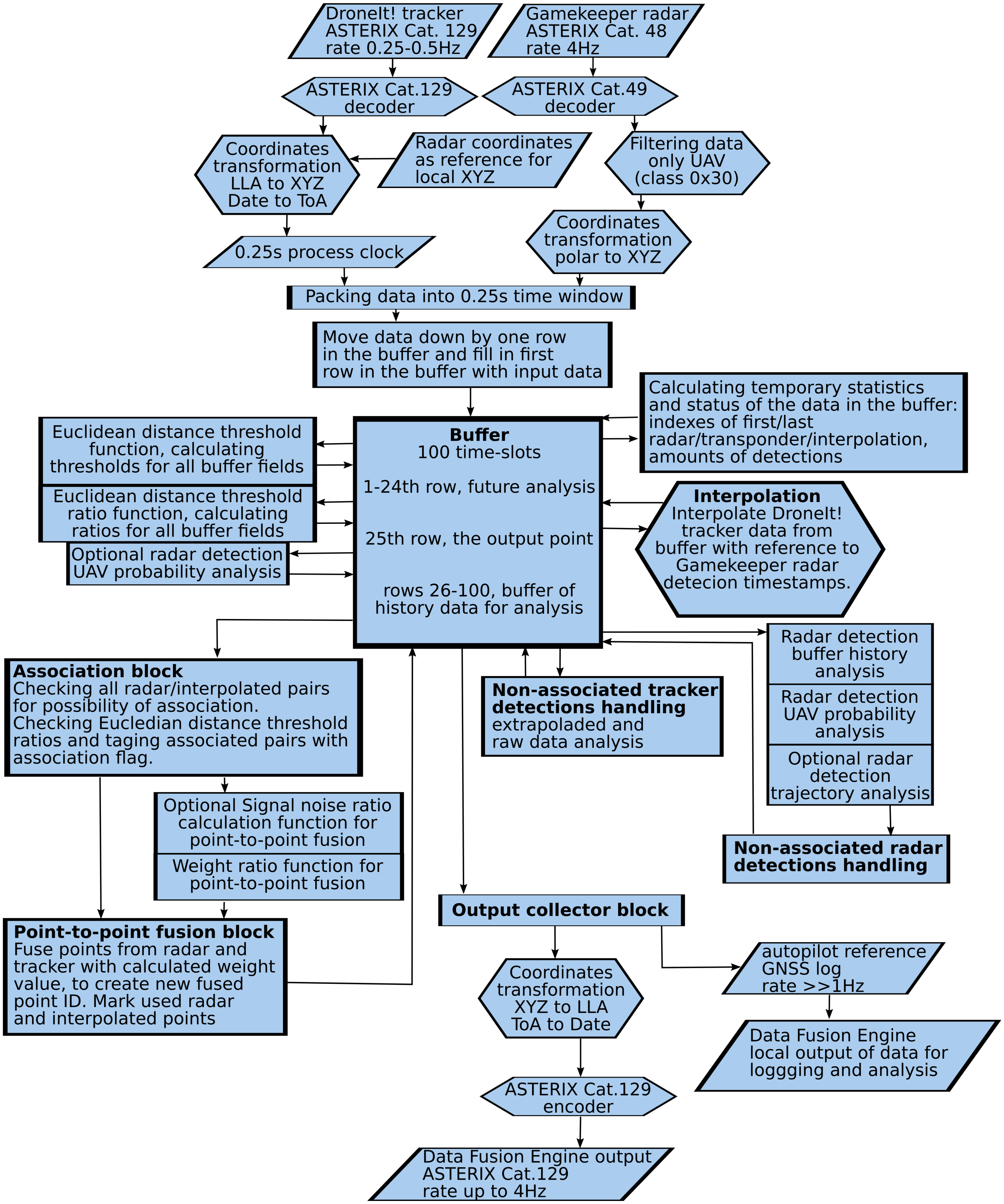

Figure 8. Data Fusion Engine algorithm overview.

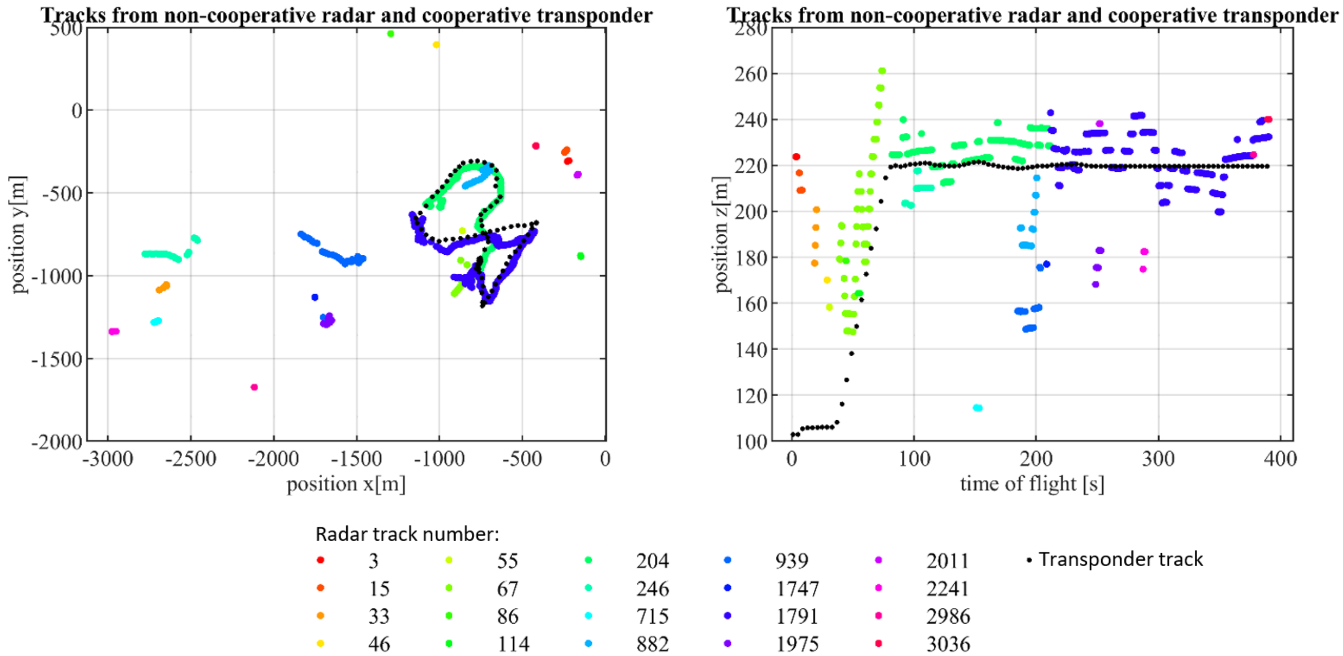

Figure 9. Tracks form non-cooperative and cooperative systems.

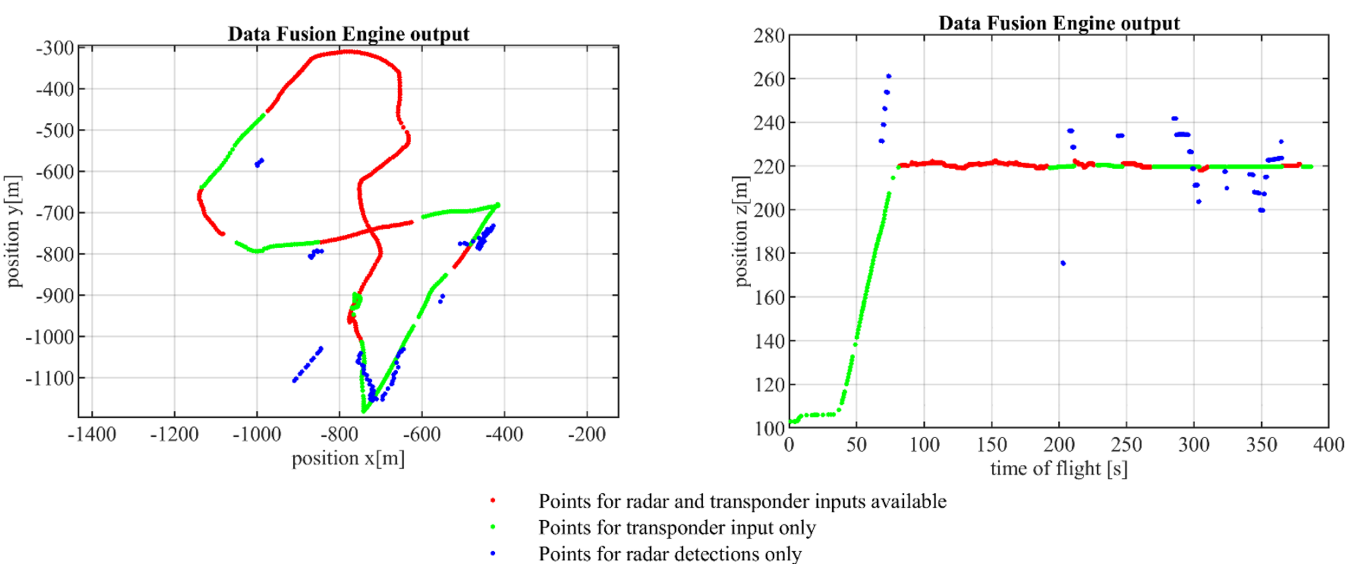

Figure 10. Data Fusion Engine results.

protocol ASTERIX [18, 19].

Cooperative data input—The cooperative data stream is encoded into ASTERIX category 129 [18] which is designed for reporting UAV's position, altitude, identification information, flight plan information, time of transmission of the message, GNSS status and operational risk level. This data is generated and streamed from Airbus' Drone-it! system with rate in the range 0.25 to 0.5 Hz. For the purposes of track-to-track data fusion engine, the position, altitude, drone ID and time fields are used. That data is fed directly to track-to-track data fusion engine without additional processing. Therefore positioning error is directly related to the quality of GNSS data.

Non-coperative data input—The non-cooperative data stream is encoded into ASTERIX category 48 [19] which is designed for transmission of mono-radar data. Aveillants Gamekeeper radar generates and streams processed output with a rate of 4 Hz. The track-to-track data fusion engine is processing following records: slant range (Rho) to the target, direction (Theta) to the target, target altitude measured by a 3D Radar, absolute time stamping of transmission of message, track number, and classification data. In the tested version of the system the radar position, elevation, and bearing were entered manually.

Data normalization—ASTERIX category 48 and 129 data streams are decoded into human-readable XML files. In order to optimize a data volume, unused variables are erased and XML structure is corrected. Later, data from both sources is normalized in a pre-processor to get the same input format for the data association and fusion blocks. In case of the radar data, local polar coordinates must be transformed into local Cartesian coordinates with the reference point at the radar position. Drone-it! coordinates also need to be transformed from Latitude, Longitude, Altitude (LLA) coordinate system into local Cartesian coordinates with the radar position as the common reference.

Data buffer—As previously described data from radar and Drone-it! differs in output frequency (4Hz vs 0.5Hz). In the data-fusion algorithm incoming data from the stream is grouped into 0.25 second time-slots and then inserted into the buffer. The data buffer length is a design parameter and in the tested version of the data fusion engine has fixed value of 100 time-slots, which corresponds to 25 seconds. The buffer is arranged to keep the latest history of data in a pre-allocated space (moving window), such that when new data comes, the oldest data is removed from the buffer. Another design parameter of the system is a fixed system latency. In the presented version of the data fusion engine, the fixed latency is set to 25 time-slots (6.25 seconds). Such latency parameter allows to avoid extrapolation of Drone-it! positions, which can led to significant number of outliers and poor system performance when taking into account agility of tracked vehicles. During the experiment, the 6.25 seconds latency was assumed as acceptable by the end-user, however future work is planned to reduce overal system latency.

In addition, the transponder data is interpolated in order to match 4Hz radar output rate. Interpolation is made using a piece-wise cubic Hermite interpolating polynomial method [20].

Association block—Next, the sensors data is passed to the Association block. First Euclidean distance threshold function 6 is applied. The input to this function is all slant ranges from radar detection and radar position. Based on this, the distance threshold parameter is calculated as the output, and forwarded to the buffer for further processing in association block. A default distance threshold function is a design parameter. This paper uses the threshold function presented in Figure 6, designed based on empirical results.

Next function is the Euclidean distance threshold ratio function. Inputs for this function is the number of previous distances within the distance thresholds value taken from the buffer. Default distance threshold ratio is 0.9, and is a design parameter. For all of listed functions, the main output is an acceptance flag for association of a certain pair of processed radar and transponder points. Based on all results from the pre-association functions, the decision about association is made in this block. If points become associated, then both radar and tracker point detections in the buffer gets the association flag set, which is then stored in the buffer. All of the parameters are calculated from the oldest to the youngest point in the buffer at every step time slot. Using this solution all of the calculated parameters are updated at each step of buffer.

Before associated points will be fused, there is need to calculate correct fusion parameters in order to generate a final output data point. Default test weight ratio for weighted average used for first prototype version of the system was 1 for radar and 10 for transponder, which is a design parameter fitted to noise characteristics of the input data. As the result of this operations, new fused point is created/updated and stored into the buffer in every step of the buffer.

Non-associated radar detections handling—After association and fusion processing, the reminder of the radar detections are analyzed. Algorithm is looking into the history data inside of the buffer from the oldest to youngest time-slot. All available points inside of the buffer, checked from the oldest time-slot, with non-zero UAV probabilities and the same track number are counted for each time-slot. UAV probabilities comes form Gamekeeper processing system, and are part of radar input for fusion system. If track number exist in the buffer for longer than 8 seconds then is considered as detected UAV or other flying object and will be forwarded as the system output.

Non-associated transponder detections handling—In case of non-associated transponder/interpolated detections points from interpolation process are forwarded to the system output. The only special case of handling these points is when non-associated transponder/interpolated detection is found at the close neighborhood of associated radar and transponder/interpolated detection, then this point is omitted in the system output. The closest neighborhood is defined as the 4 seconds time frame (design parameter), forward and backward, from each non-associated transponder/interpolated detection in the buffer.

Output collector block—The block task is to check all of the processing outputs saved to the buffer and formulate data for the output. Data for the live output is generated from the 25^{th} time-slot in every algorithm iteration and can be forwarded to other users or used to create movie for algorithm work analysis. The local Cartesian coordinates have to be transformed back into LLA coordinates system for the end user. In case of fused data, all new fused points are getting new track ID numbers. In the presented results, new track ID numbers are constructed by adding the transponder track number multiplied by 10000 to the radar track number (current maximum limit of radar ID number is 9999). Non-associated radar and transponder processed points tracks number remains original. This block also encodes processed data back into binary protocol ASTERIX Category 129.

4. EXPERIMENT

The experiments were performed in an ex-RAF Airfield at Deenethorpe, Great Britain, 15 - 19 October 2018. The trial equipment included:

- Aveillant Gamekeeper radar 16U
- Airbus Drone-it! system
- Aveillant's test multirotor UAV DJI Inspire as non-cooperative target
- ENAC's fixed wing sUAS as a cooperative target
- Unifly's UTM system

Metrics

A set of metrics was chosen to benchmark system performance. Results expressing mean values and Standard Error of the Mean (SEM) are presented in the Table 4.

Probability of Update (PU)—value expressed in %, which is the ratio between drone detections from tracker to total drone detections from reference. Radar data and data output from fusion system are generated roughly up to 4 Hz. Reference data is provided in 1 Hz, and for calculation of PU, this data was interpolated and up-rated to 4Hz.

Position Error (ePos)—value expressed in meters, which is defined as

$$ePos = ||pos^T - pos^R)||_2, \quad (1)$$

where pos^T is Tracker Position, and pos^R is Reference Position. Comparison between radar and fused Position Error (ePos) in time, is presented in Figure 11.

Horizontal Position Error (ePosH)—value expressed in meters, which is defined as

$$ePosH = ||pos_H^T - pos_H^R||_2, \quad (2)$$

where pos_H^T is Tracker Horizontal Position, and pos_H^R is Reference Horizontal Position.

Vertical Position Error (ePosV)—value expressed in meters, which is defined as

$$ePosV = ||pos_V^T - pos_V^R)||_2, \quad (3)$$

where pos_V^T is Tracker Vertical Position, and pos_V^R is Reference Vertical Position.

Experimental data examples

Figure 9 shows 393 seconds of the raw radar data stream and reference track. Radar location is in the origin of the coordinate system. The color scale represents track numbers assigned by radar to objects detected, increasing numbers also represents time flow. A black dotted line represents reference track of the UAV flight.

In the Figure 9 tracks not created by the UAV are mainly caused by birds (other targets which can be occasionally be captured are ground vehicles, moving trees or other moving objects in the range of radar). Left plot in Figure 9 shows the X-Y 2D view of the system input and right plot shows the time-of-day and altitude (Z) of the system input.

Figure 10 shows the output of data fusion engine. Data is presented in color for records where input from both systems was available, as well as for when only transponder or only radar input was available.

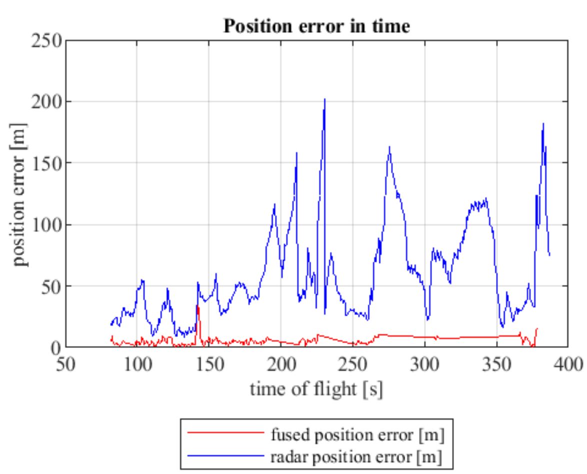

Figure 11. Position error in time.

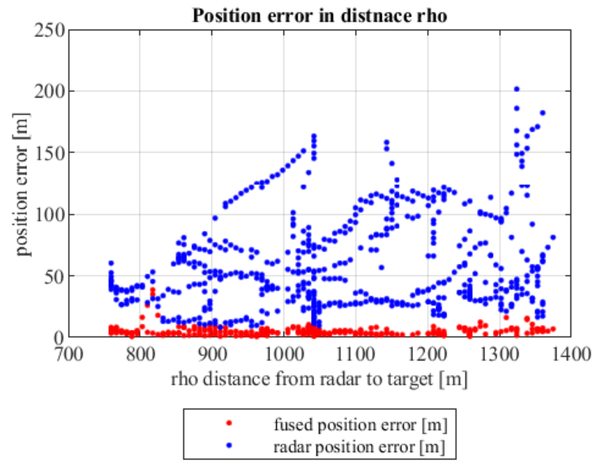

Figure 12. Position error in distance rho.

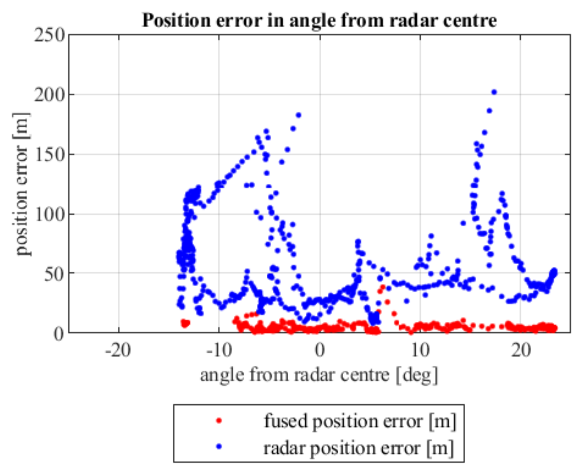

Figure 13. Position error in angle from radar centre.

The 3D position error in time, as well as as its improvement after Data Fusion is presented in Figure 11. As the improvement of data fusion output over only cooperative track, can be considered increased frequency of output, robustness and continuity of the output in case of gaps in cooperative track. From all of fused point pairs for this flight, any of radar detections wasn't a bird-detection.

The Figure 12 shows no clear correlation of radar error with distance to the target in the presented range. The Figure 13 suggests that angle from the radar's center may have influence on the size of the error. However, it could be argued that the error can be caused by the UAV turns, where objects Radar cross-section (RCS) changes. This higher errors on the sides from center of radar could also be caused by track seductions from radar.

The results in the Table 4 shows comparison between mean errors and SEM for radar and fusion system output to reference. Fusion system output results in mean position error, mean horizontal position error and mean vertical position error are on acceptable level for UTM system input. The radar to reference error results obtained for this single flight are

Table 1. Comparison of mean errors and SEM for radar to reference and fusion system output to reference.

Metric	Fused to ref.	Radar to ref.	Change
PU, 4Hz ref. (%)	48.41	41.61	6.80%
mean ePos (m)	5.1305	59.6589	91.40%
SEM ePos (m)	0.2298	1.6147	85.76%
mean ePosH (m)	5.0349	58.6570	91.41%
SEM ePosH (m)	0.2320	1.6286	85.75%
mean ePosV (m)	0.6699	7.9251	91.54%
SEM ePosV (m)	0.0278	0.2401	88.42%

higher than errors calculated in previous July tests performed before for longer period of time with higher amount of flights, then this results in case of ePosH were on the level of 30 meters and ePosV at 12 meters. The results in the Table 4 for the performance metrics are only presented from one drone flight that lasted for a duration less that 5 minutes. A wider data sets is required to obtain a better statistical significant measure of the performance. Thus for example positional errors of the tracks obtained with the radar can typically be affected by multipath, target fading and impact on signal quality due to presence of clutter and interference leading to outliers in the fused track output. Future work will extended the analysis to larger datasets to better understand the limits of the underlying performances of both the individual tracking system and that of the fused output.

5. SUMMARY

This paper presents a Data Fusion Engine which uses radar and transponder data as input. Presented metrics show mean ePos improvement of 91%, and 6.8% improvement of Probability of Update.

ACKNOWLEDGMENTS

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BIOGRAPHY

Krzysztof Cisek *received his M.Sc. (Eng.) degrees in control engineering and robotics from the Wrocaw University of Science and Technology, Faculty of Electronics, in 2011. From 2011 to 2014 he was software and robotics engineer in R&D Department in Flytronic Sp. z o.o. (WB Group), leading Polish constructor and R&D center for Unmanned Aerial Vehicles and Systems for defense sector, Gliwice, Poland. From 2014 he is research fellow and engineer at Unmanned Aerial Vehicle Laboratory, Autonomous Marine Operations and Systems (AMOS), Department of Cybernetics at Norwegian University of Science and Technology. His research interests are in the areas of software/hardware development and integration of unmanned aerial systems, ultra wideband location systems and data fusion. This work is supervised by professor Tor Arne Johansen.*

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